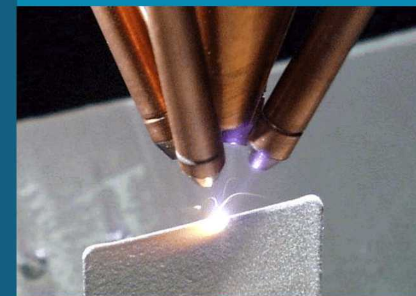
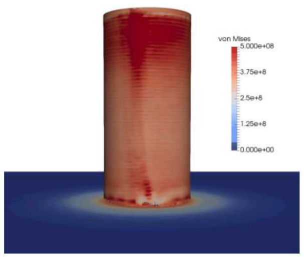
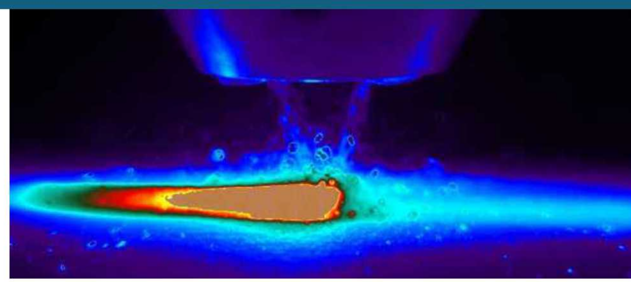
SAND2018-8243C

Predicting Baseplate Preheating Effects on Residual Stress and Microstructure in LENS Parts







Kyle Johnson, Joe Bishop, Phil Reu, Theron Rodgers, Shaun Whetten, Mike Stender, and Lauren Beghini

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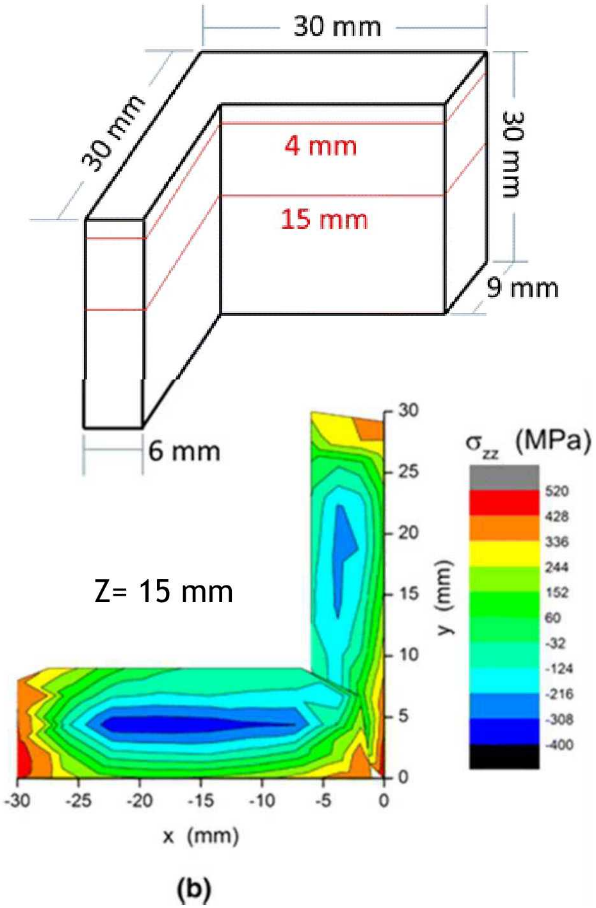
Outline

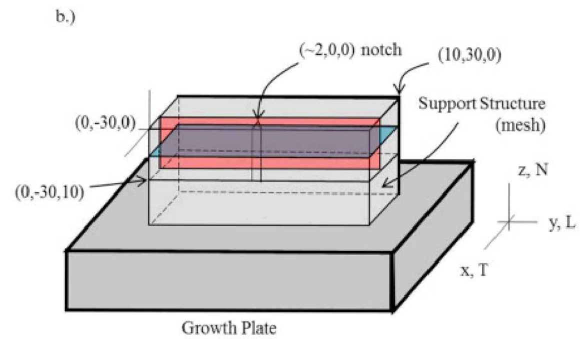
- Background and Motivation
- Thermal and Solid Mechanics Methodology and Results
- Comparison to DIC Experiments
- Microstructure Modeling Methodology and Results
- Conclusions and Future Work

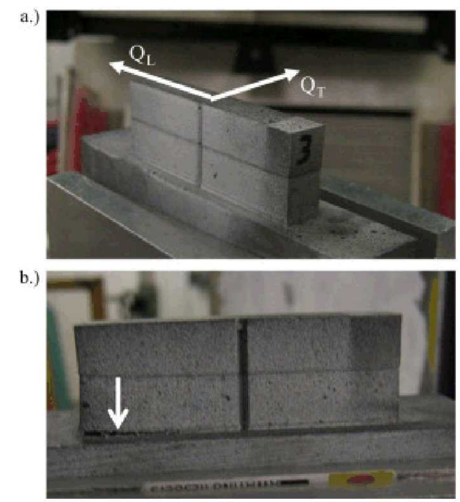
High Thermal Gradients in AM Produce High Residual Stresses



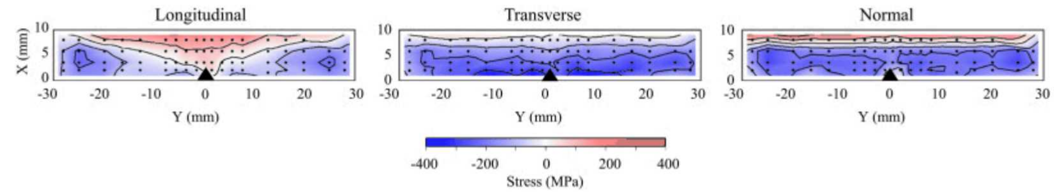
316L Stainless Steel Powder Bed

Wu et al., Metall Mater Trans A 2014





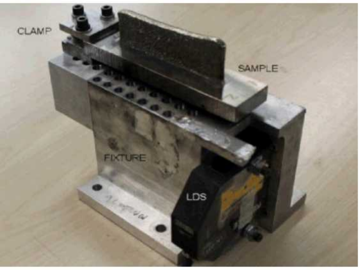
*Stress measured at blue plane

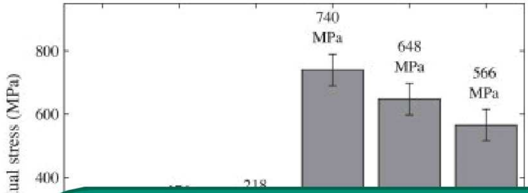


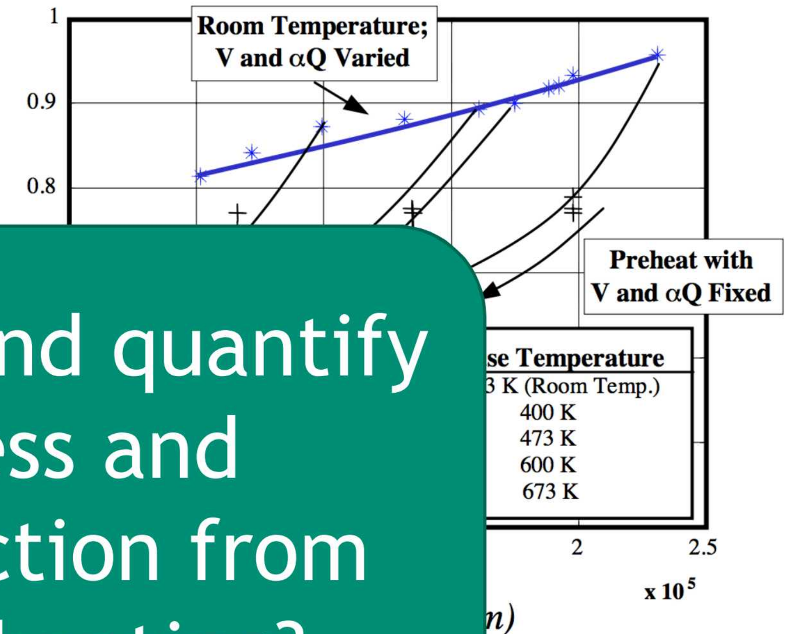
17-4 Stainless Steel Powder Bed

Brown et al., Mat Sci Eng A 2016

Thermal Gradients Can Be Controlled (Somewhat)







Denlinger et al., J.

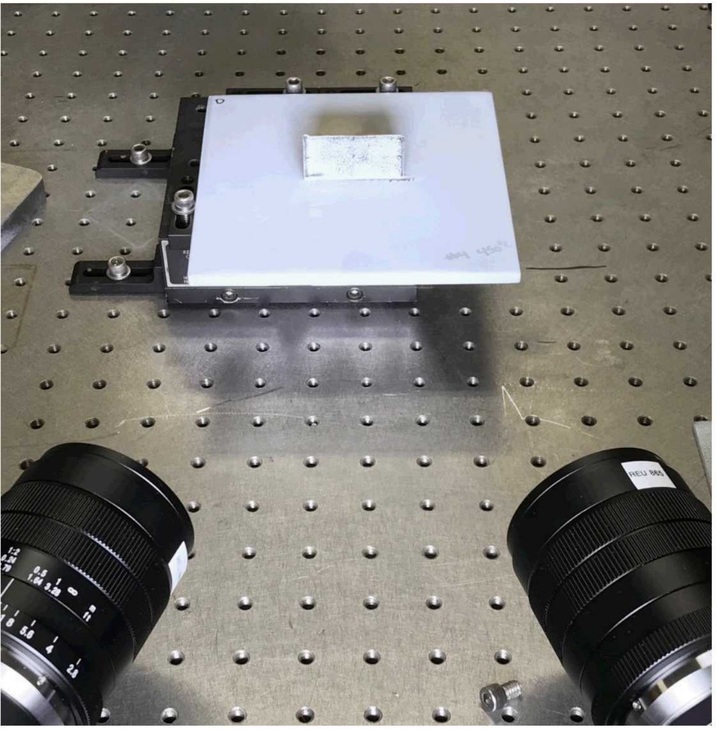
Can we predict and quantify residual stress and distortion reduction from baseplate preheating?

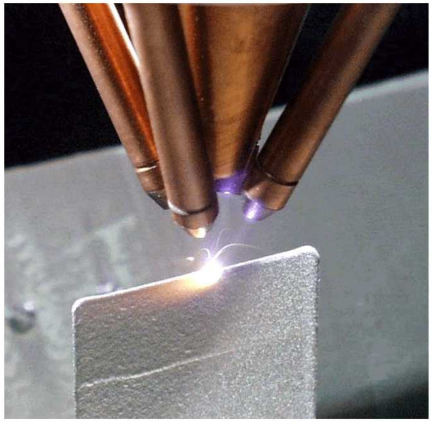
FS Proceedings 2000

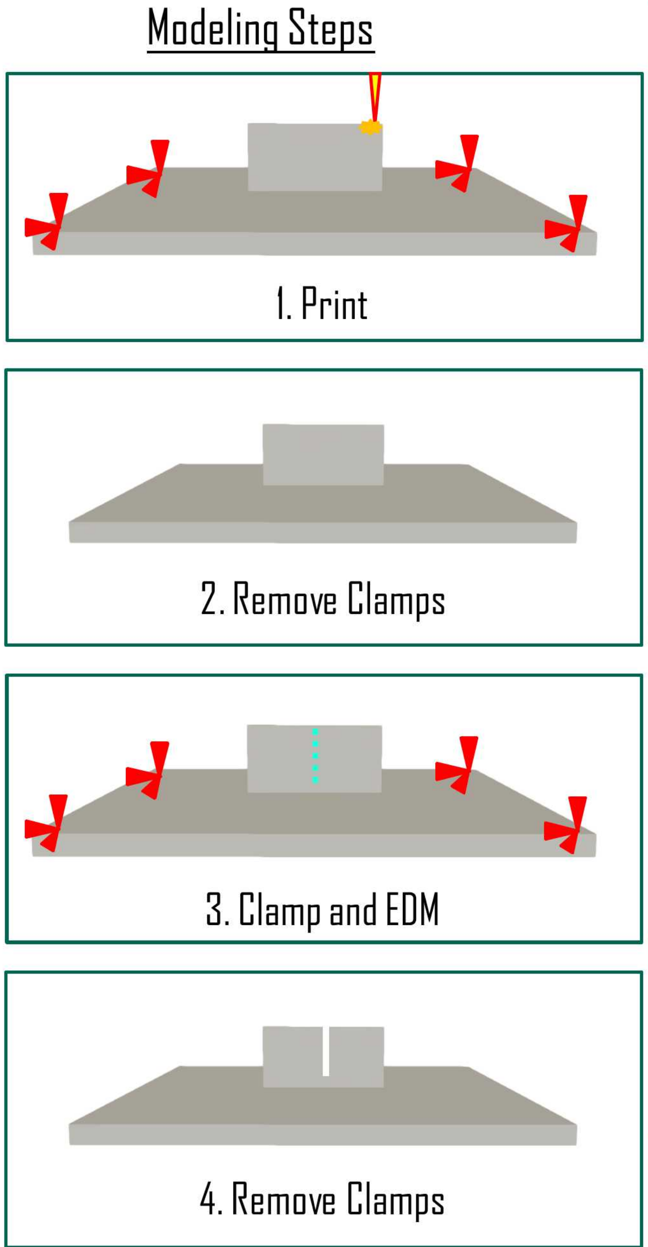
Inter-layer dwell times can change residual stresses

Baseplate preheat reduces thermal gradients

Baseplate Preheat Study Approach







- Thin wall LENS build
  - 0.95 mm laser size
  - 400 W
  - 7.5mm/s laser speed
  - Serpentine path, 2 passes per layer
- Baseplate at room temperature and 450C
- EDM cut down centerline of wall for stress relaxation
- Digital Image Correlation (DIC) to measure distortion before and after cut

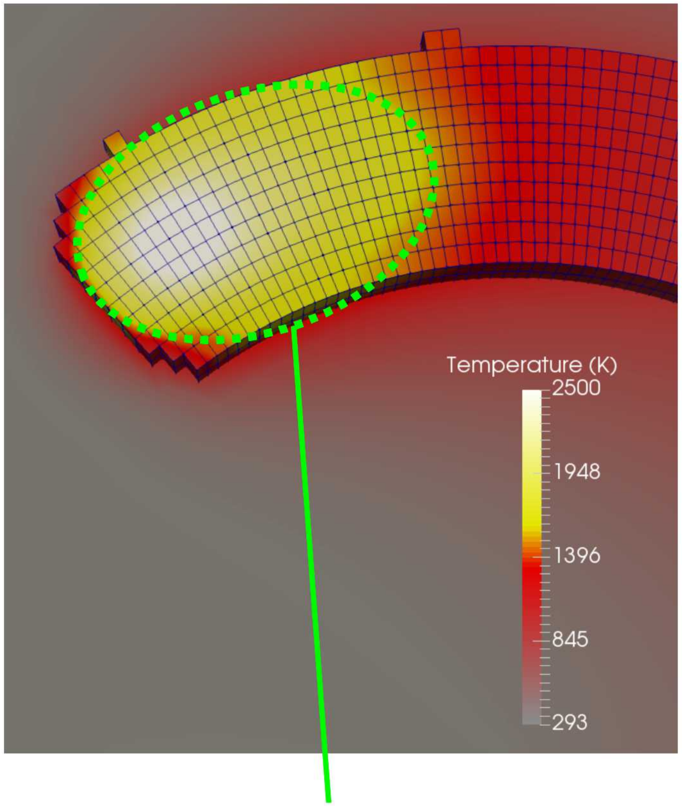
Thermal Modeling Methodology

Pre-meshed part is initialized with "inactive" elements. Baseplate elements are active.

Laser heat source is scanned according to input path

Elements are activated by a thermal conductivity increase once they reach melt temperature

Conduction, convection, and radiation are considered.



Approximate Melt Pool

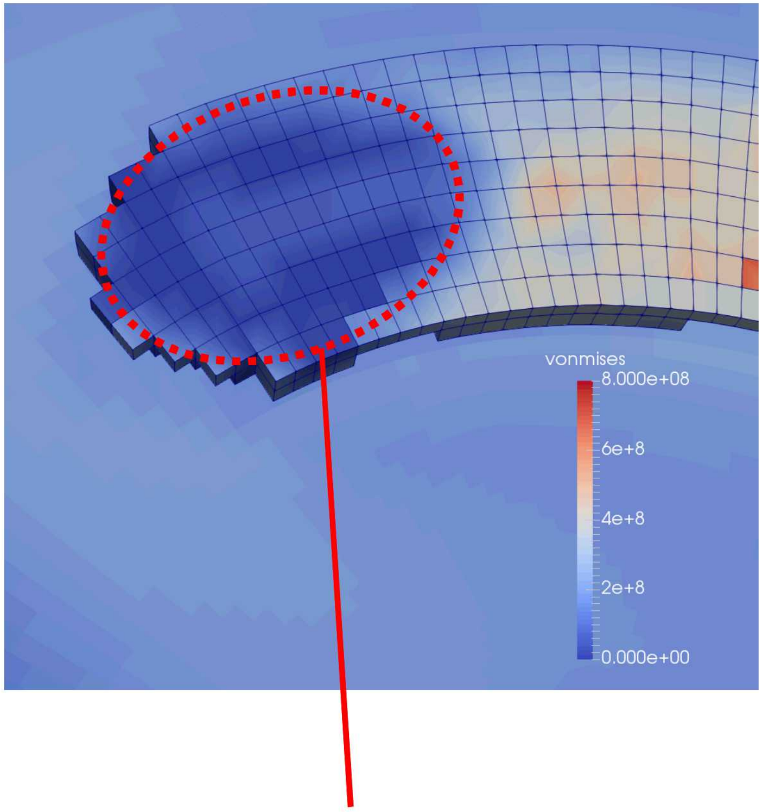
Solid Mechanics Modeling Methodology

Pre-meshed part is initialized with "inactive" elements. Baseplate elements are active.

Thermal output file is read at every time step to provide temperatures

Elements are activated once they reach melt temperature

Residual stress builds as elements contract upon cooling and build thermal strain



Approximate Melt Pool
(~zero stress)

Bammann-Chiesa-Johnson (BCJ) Material Model

- Temperature and history-dependent viscoplastic internal state variable model
- Stress is dependent on damage ϕ and evolves according to

$$\dot{\sigma} = \left(\frac{\dot{E}}{E} - \frac{\dot{\phi}}{1-\phi}\right)\sigma + E(1-\phi)(\dot{\varepsilon} - \dot{\varepsilon}_p)$$

- Flow rule includes yield stress and internal state variables for hardening and damage

$$\dot{\varepsilon}_p = f\,sinh^n\left(\frac{\frac{\sigma_e}{1-\phi} - \kappa}{Y} - 1\right)$$

- Statistically stored dislocations are represented by isotropic hardening variable κ

$$\kappa = c_{\varepsilon_{ssds}} b\mu(\theta)\sqrt{\rho_{ssds}} \qquad \dot{\rho}_{ssds} = \left[\frac{k_1}{L_s} + \frac{k_2}{L_g} - R_d(\theta)\rho_{ssds}\right]\dot{\varepsilon}_p$$

- Geometrically necessary dislocations are represented by a misorientation variable ζ

$$\dot{\zeta} = \frac{\zeta}{\mu(\theta)}\frac{d\mu}{d\theta}\dot{\theta} + h_\zeta \mu(\theta)\left(\frac{\zeta}{\mu(\theta)}\right)^{1-\frac{1}{r}}\left|\dot{\varepsilon}_p\right|$$

- The hardening variable κ evolves in a hardening minus recovery form.

$$\dot{\kappa} = \frac{\kappa}{\mu(\theta)}\frac{d\mu}{d\theta}\dot{\theta} + \left[H(\theta)\left(1 + \frac{\zeta}{\kappa}\right) - R_d(\theta)\kappa\right]\dot{\varepsilon}_p$$

(Bammann *et al.* 1993, Brown and Bammann 2012)

Room Temperature and 450C Builds Produce Different Thermal Histories

Room Temperature Baseplate

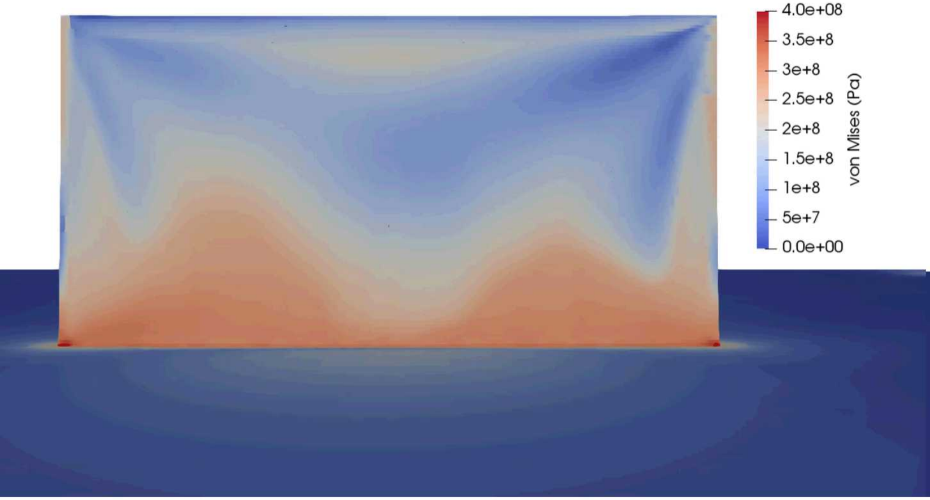
450C Baseplate

Different Thermal Histories Produce Different Stress States

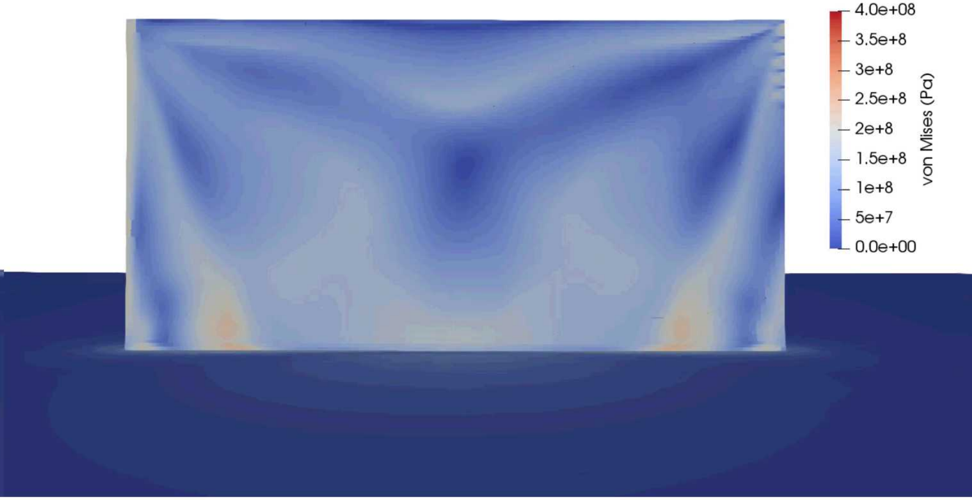
Room Temperature Baseplate

450C Baseplate

EDM Relieves Stress and Causes Distortion

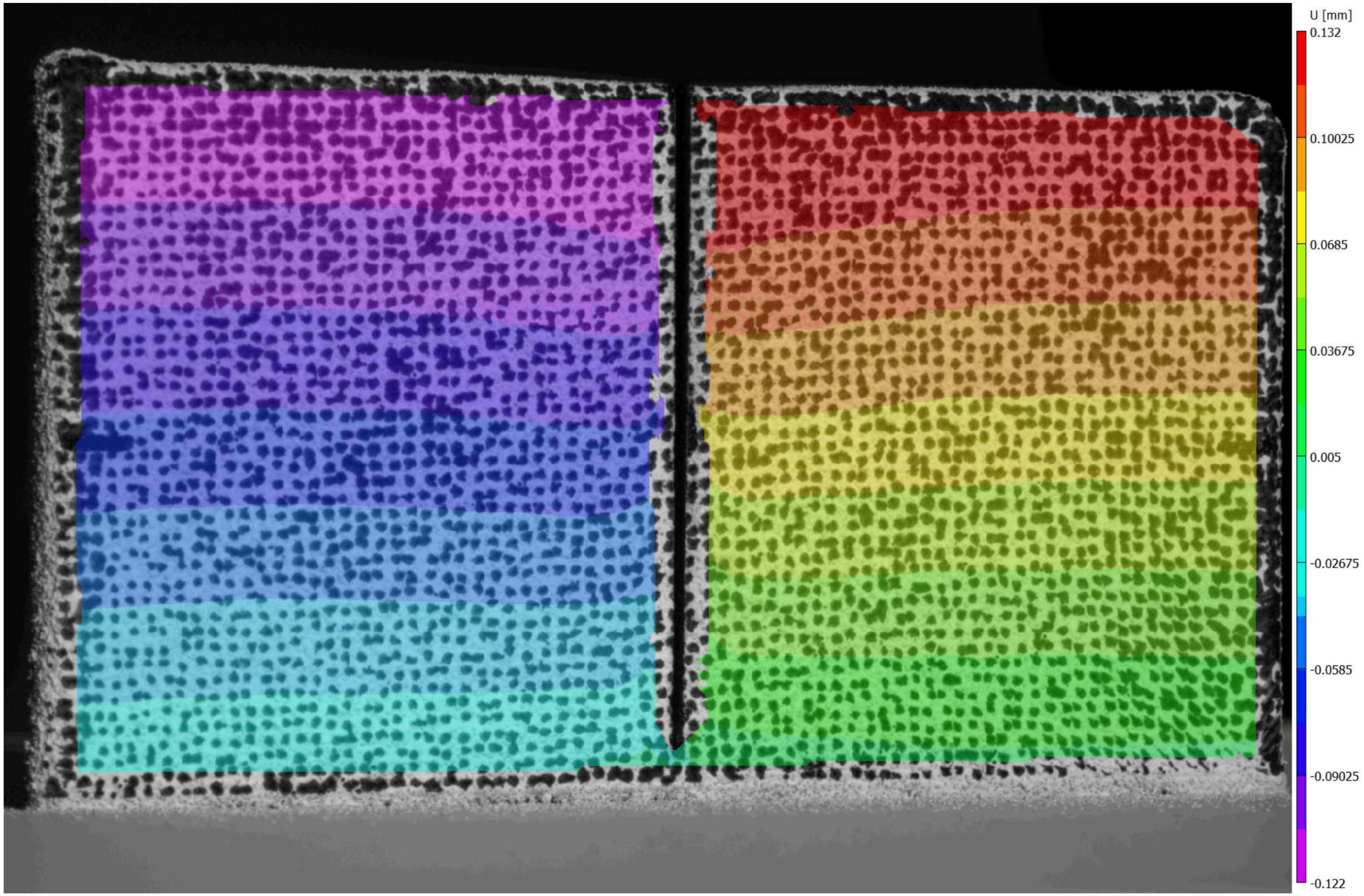


Room Temperature Baseplate

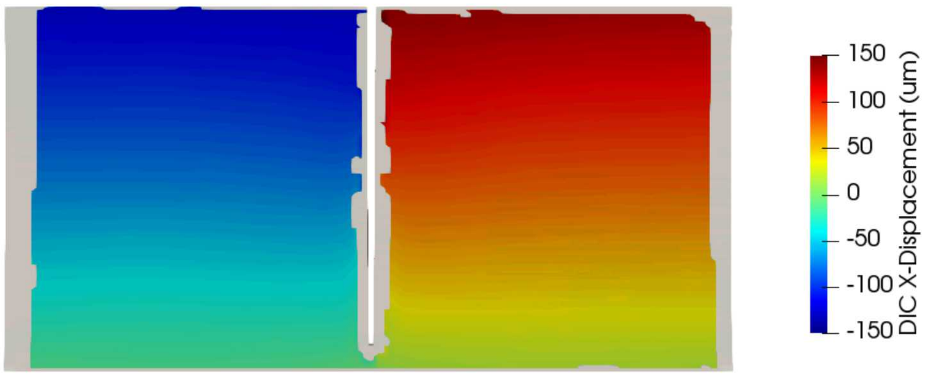


450C Baseplate

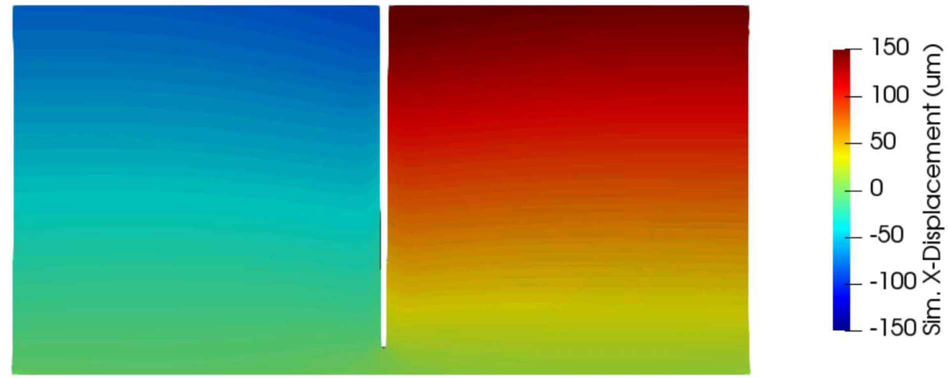
Wall Shows Visible Displacement After Cut



Room Temperature Build DIC Data Compares Well With Simulation Results

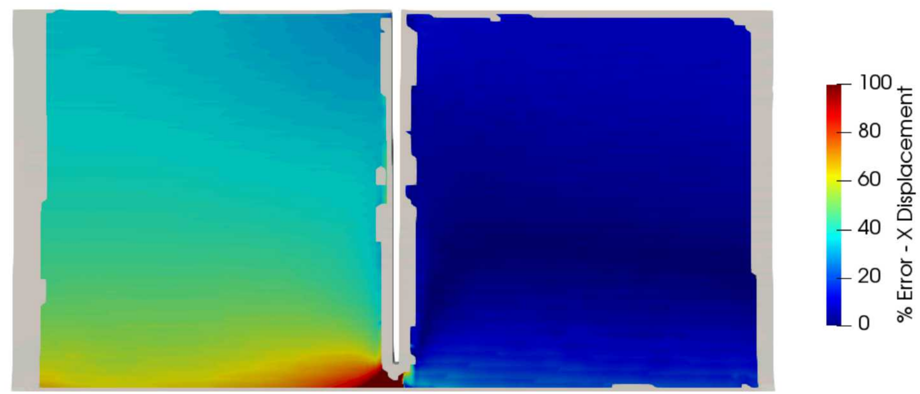


X-Displacement DIC Results Overlaid on Model

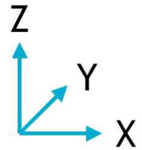


X-Displacement Simulation Results

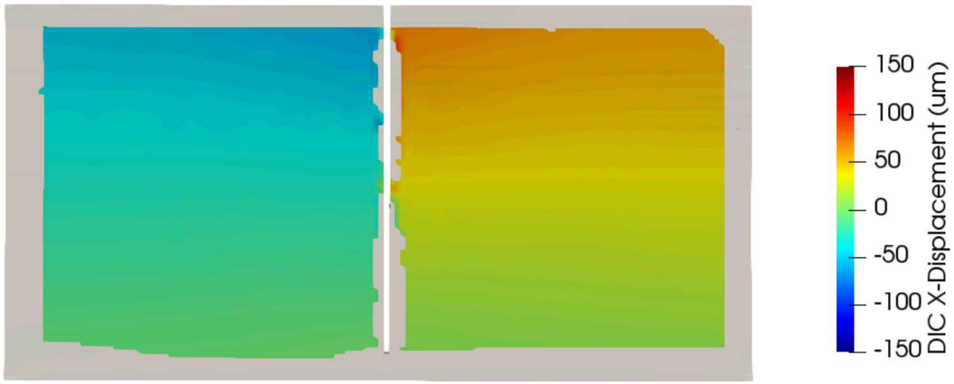
$$\% \, Error = \frac{|\Delta x_{sim} - \Delta x_{exp}|}{\Delta x_{exp}}$$



Percent Error



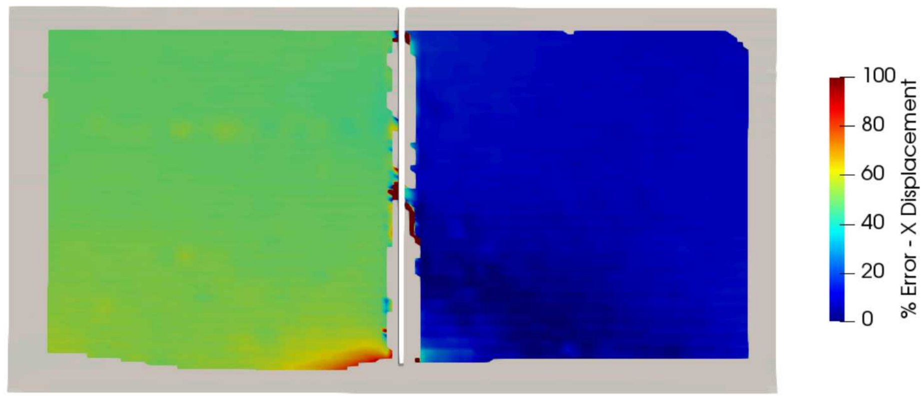
450C Build Shows Reduced Distortion Compared to Room Temperature Baseplate



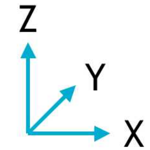
X-Displacement DIC Results Overlaid on Model

X-Displacement Simulation Results

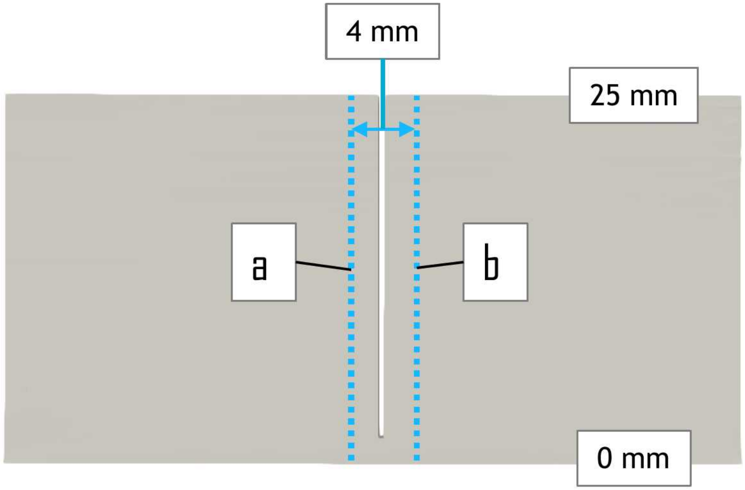
$$\%\ Error = \frac{|\Delta x_{sim} - \Delta x_{exp}|}{\Delta x_{exp}}$$



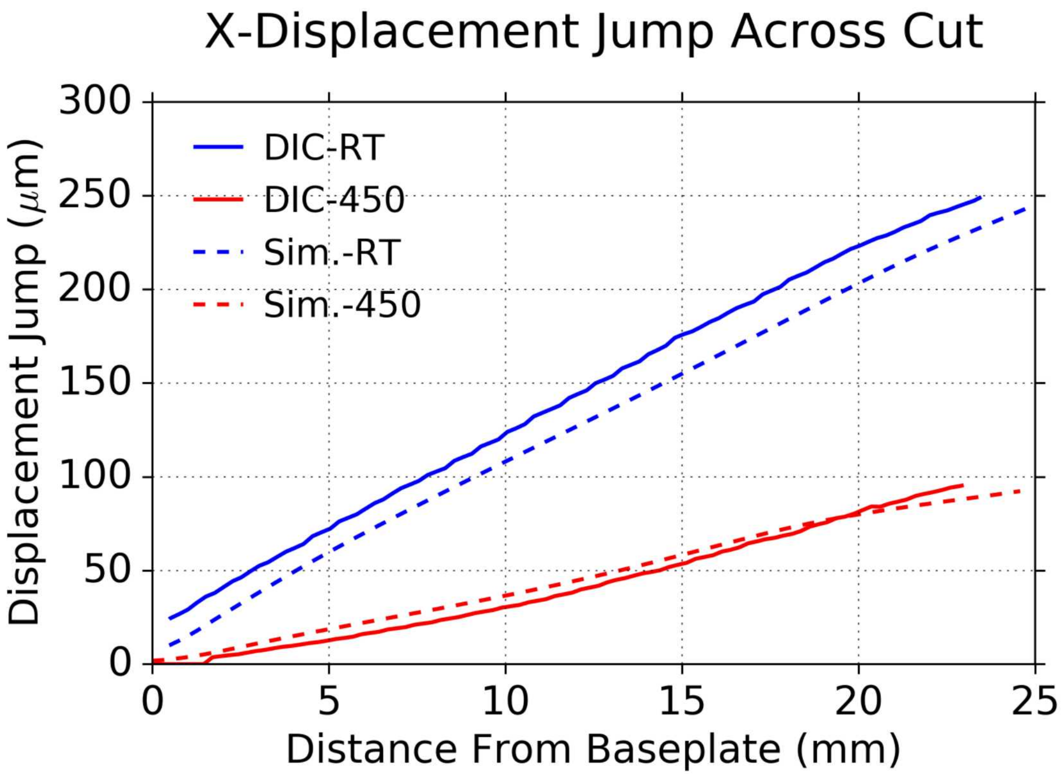
Percent Error



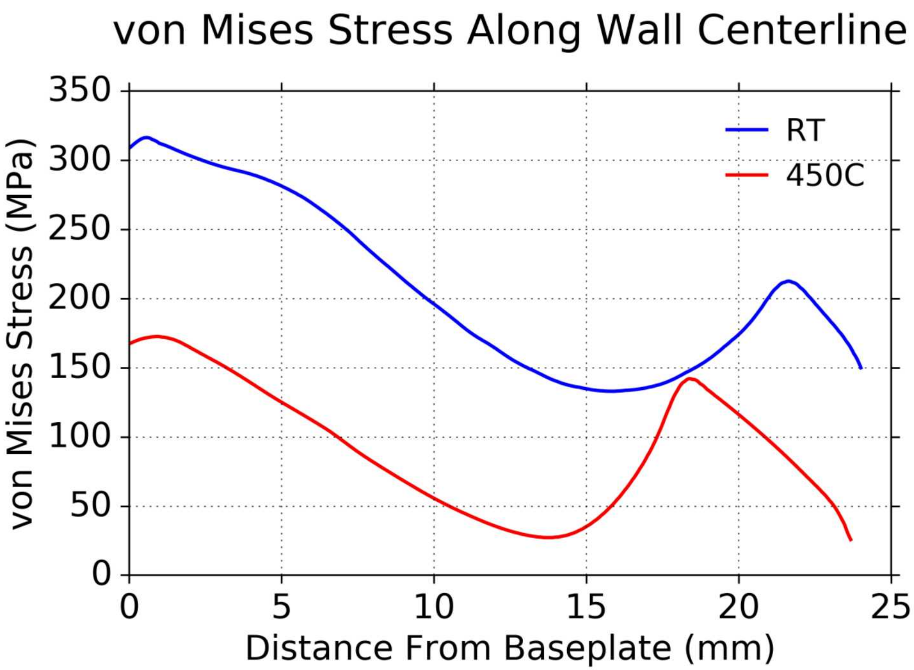
Displacement Jump Across Cut Compares Well to Experiments

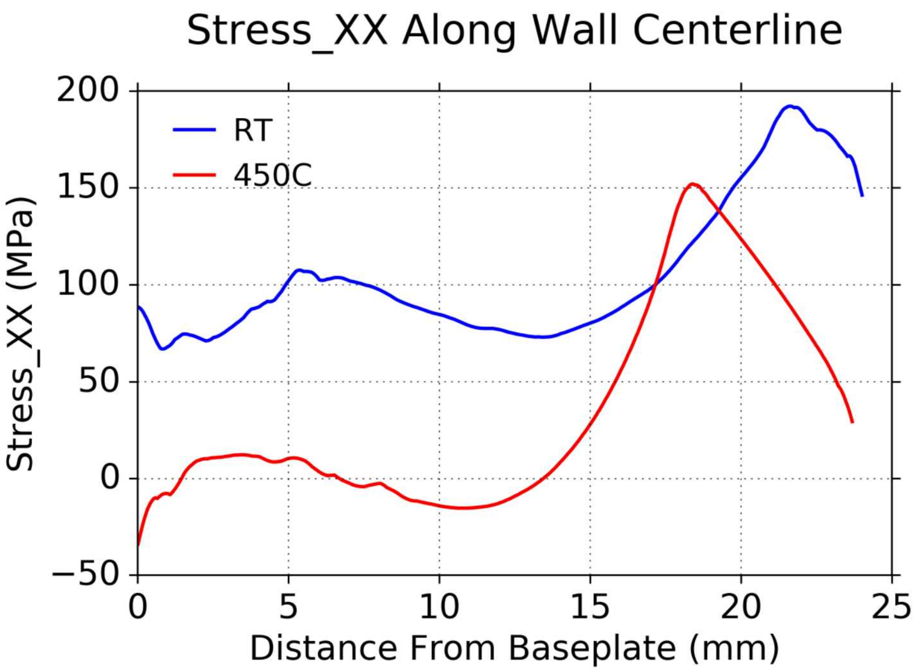


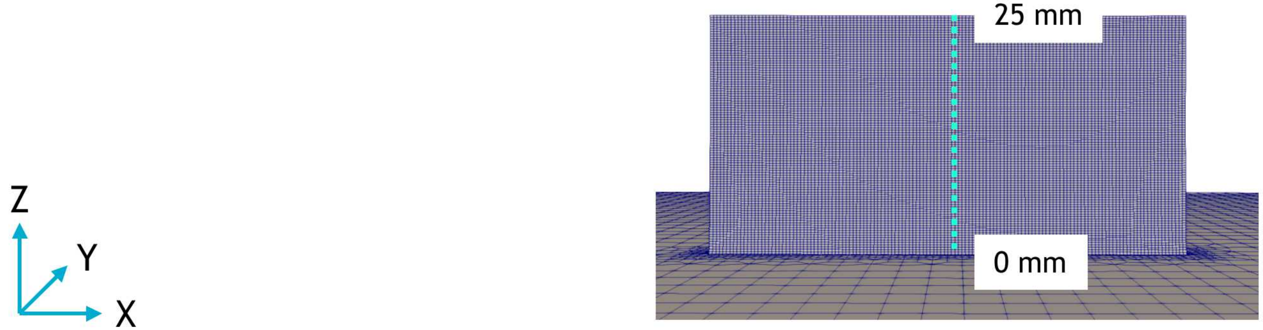
$$Displacement\ Jump = \Delta x_b - \Delta x_a$$



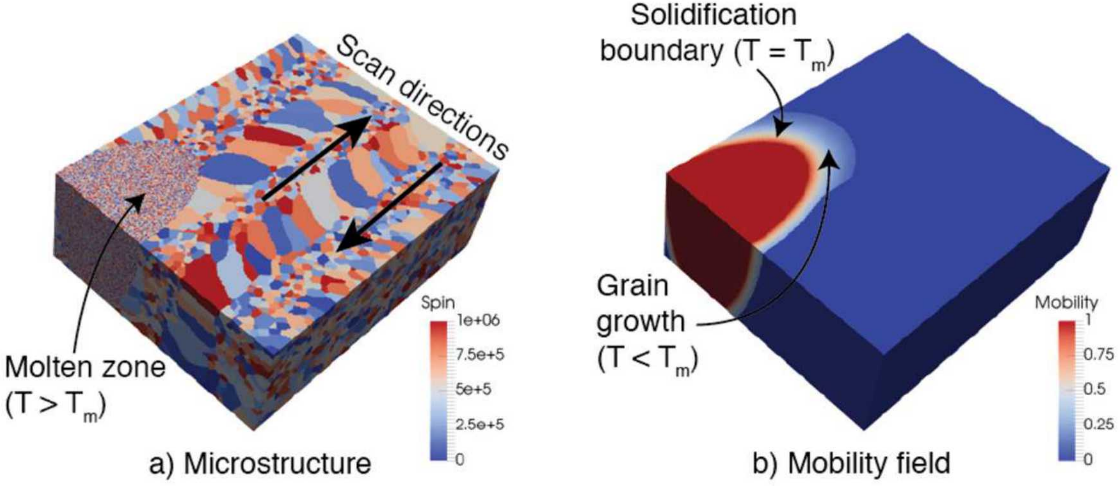
Residual Stress Along Wall Centerline is Significantly Reduced by Preheating Baseplate







Microstructure Prediction in Stochastic Parallel PARticle Kinetic Simulator (SPPARKS)



Johnson, Rodgers et. al, Computational Mechanics 2017

$$M(T) = M_o \exp\left(\frac{-Q}{RT}\right)$$

$$P = \begin{cases} M(T)\exp\left(\frac{-\Delta E}{k_B T_s}\right), & if\ \Delta E > 0 \\ M(T), & if\ \Delta E \leq 0 \end{cases}$$

- Temperature history is used as material state in SPPARKS
- Captures bulk heating effects on microstructure
- Rodgers *et al.*, “Simulation of metal additive manufacturing microstructures using kinetic Monte Carlo,” *Computational Materials Science 2017*
- Rodgers, Bishop, and Madison, “Direct numerical simulation of mechanical response in synthetic additively manufactured microstructures,” *MSMSE 2018*

Incorporating Material-Dependent Parameters

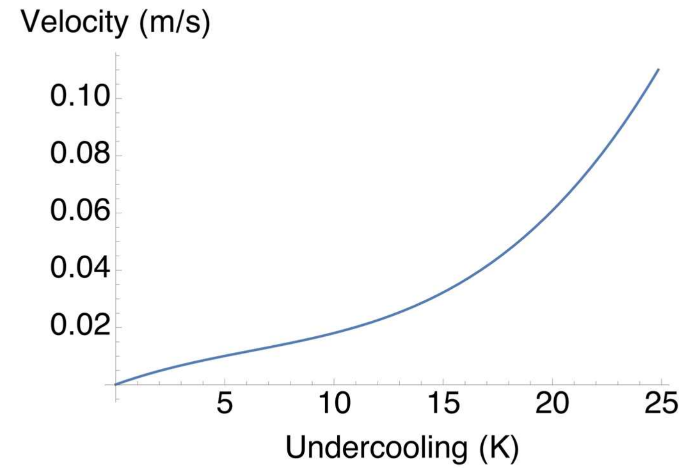
Nucleation site density, N_0, is the number of possible nucleation sites per m^3 (typically 10^{12}-10^{15} m^{-3}). Implemented by allowing a fraction of grain IDs to survive the liquid->solid transition without changing grain ID.

$$N_{frac} = N_0 \Delta x^3$$

Undercooling ($\Delta T = T_l - T$)-dependent **solidification front velocity, $\boldsymbol{V}(\Delta \boldsymbol{T})$.**

$$V(\Delta T) = a(\Delta T)^3 + b(\Delta T)^2 + c(\Delta T) + d,$$

the coefficients are determined from dendrite-scale solidification simulations or experiments.

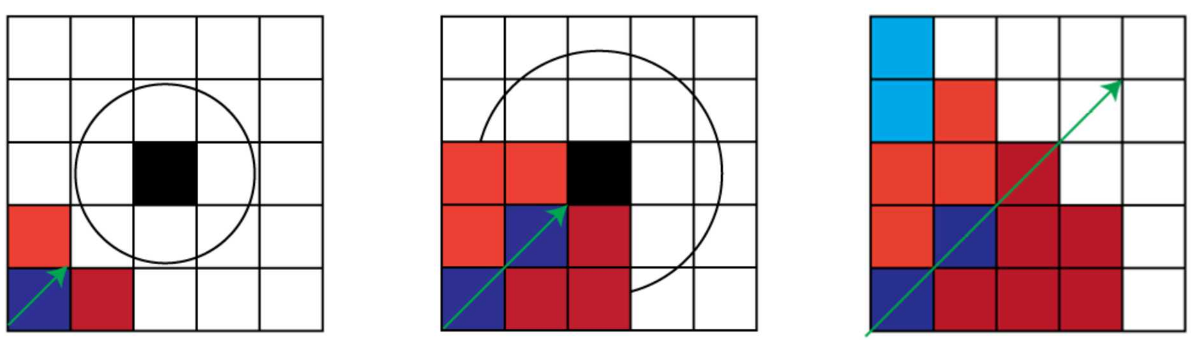


Implemented by tracking solidification front distance per site,

$$\mathrm{D}(x,t) = \sum_{i=0}^{t} V(x,t) * \delta t,$$

where δt is a constant timestep.

When 1 or more solid neighbor sites are within $\mathrm{D}(t)$, the active site solidifies and probabilistically joins a solid neighbor.



Video of Microstructure Build

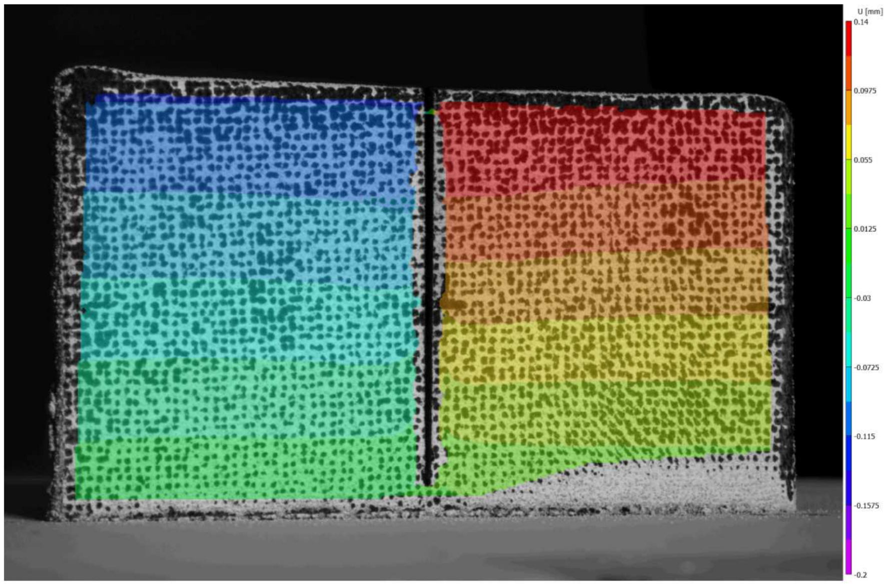
Room Temperature Baseplate

450C Baseplate

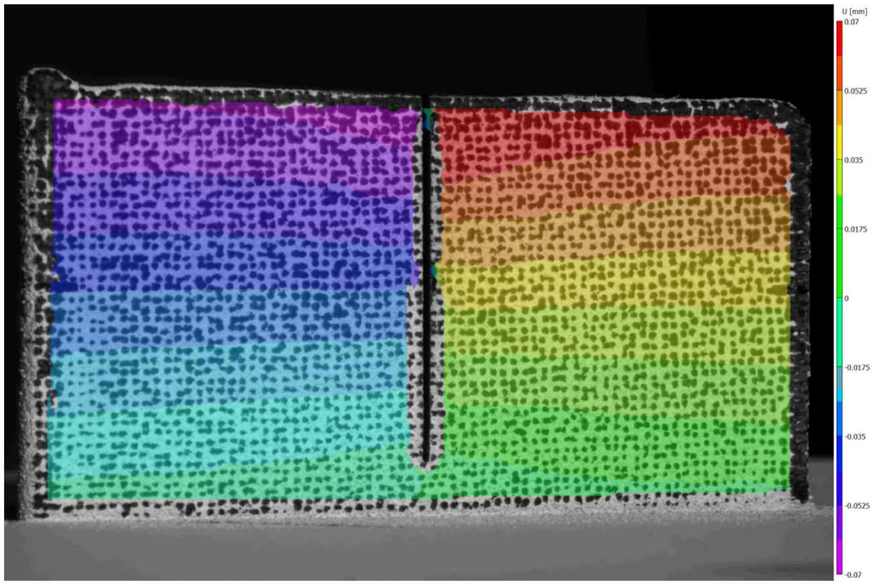
Summary and Conclusions

- Build and machining of a thin wall build was performed on room temperature and 450C baseplates
- Distortion predictions compared well with measured DIC data, giving more confidence in residual stress predictions
- Residual stress models showed large decrease in stress due to 450C baseplate preheat – approximately 50%
- Microstructure model showed a noticeable change in grain morphology due to baseplate preheat

QUESTIONS?



Room Temp



450C

DIC Setup

Cameras- 12MP Point Grey Grasshoppers.

Lenses-Schneider 17mm.

Cal Target Correlated Solutions 5mm(s/n7DD04A003)